Renewable and Sustainable Energy Reviews 98 (2018) 163–178

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Harvest green energy through energy recovery from waste: A technology review and an assessment of Singapore

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ARTICLE INFO

Keywords:
Waste to energy
AD
Gasification
CHP
Incineration

ABSTRACT

The increasing challenge in waste disposal and high dependency on imported fossil fuel has compelled Singapore to make continuous efforts in advancing waste to energy (WTE) technology, which could ensure sustainable development on one hand and energy resilience on the other hand. This paper summarizes the current WTE practices and research trends in Singapore, covering anaerobic digestion (AD), gasification, combustion-based biomass combined heat and power (CHP) production, and incineration, with the aim to define future perspectives of Singapore WTE application. Among the different aspects assessed, source-separated food waste (FW) and brown water present the biggest energy potential if AD is adopted instead of incineration. Given that the purity of source separated waste determines the extent of recovered energy, suggestions are made to increase the participating rate in source separation among Singapore residents, such as environmental education through social media and phone apps and proper facilities installation at household and community. Moreover, additional benefits can be credited to WTE system if the waste to material practice is also conducted on top of energy production.

1. Outlook on Singapore energy consumption

Occupying a land area of 719.1 km^2, Singapore by 2015 accommodated 5.5 million populations, which were projected to be 6.9 million by 2030 as outlined in the latest Population White Paper [1]. Singapore today ranks among the world's strongest and most competitive economies, and energy undoubtedly plays an important role in the 50 years of continuous development and growth. However, Singapore has limited natural resource and relies heavily on the import of fuels from other countries. In 2015, the total electricity generation in Singapore was around 50 TWh, 97.2% of which was contributed by the imported fossil fuel (Fig. 1). The remaining 2.8% of electricity demand was met by local energy sources, such as municipal solid waste (MSW), biomass and photovoltaic panel. [2].

According to methodologies recommended by the Intergovernmental Panel on Climate Change (IPCC), it was calculated that the grid CO_2 emission factor for 1 kWh net electricity generation was 0.4313 kg [2]. In addition, 0.00213 kg methane was released upstream, as methane escaped into atmosphere during producing, processing and transporting of natural gas. In total, 1 kWh Singapore grid

Abbreviation: AD, Anaerobic digestion; ADOS, Anaerobic digestion of organic slurry; APC, Air pollution control; BOD, Biological oxygen demand; BW, Brown water; CGE, Cold gas efficiency; CFD, Computational fluid dynamics; CHP, Combined heat and power; COD, Chemical oxygen demand; EF, Electrical conversion efficiency; FA, Fly ash; FB, Fluidised bed; FW, Food waste; GW, Global warming; GUI, Graphical user interface; HHV, High heating value; HM, Horse manure; IBA, Incineration bottom ash; IP, Incineration plant; IPCC, Intergovernmental panel on climate change; IWMF, Integrated waste management facility; LHV, Low heating value; MOF, Ministry of finance; MSW, Municipal solid waste; NEA, National environment agency; NTU, Nanyang Technological University; NUS, National university of Singapore; O&M, Operation and Maintenance; PPP, Public-Private-Partnership; R3C, Residue and resource reclamation centre; SCR, Selective catalytic reduction; SNCR, Selective non-catalytic reduction; TMTS, Tuas marine transfer station; TS, Totol solid; TWRP, Tuas water reclamation plant; VFA, Volatile fatty acid; VOCs, Volatile organic compounds; VS, Volatile solid; WRP, Water reclamation plant; WTE, Waste to energy; WTTP, Wastewater treatment plant

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https://doi.org/10.1016/j.rser.2018.09.009
Received 21 September 2017; Received in revised form 30 August 2018; Accepted 5 September 2018
Available online 18 September 2018
1364-0321/

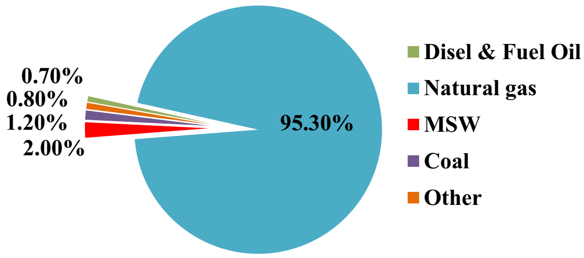

Fig. 1. Percentage contribution of different energy resources in Singapore electricity mix.

electricity would exert a global warming impact of 0.48455 kg CO_2eq. To fight for climate change as part of the international efforts, Singapore is seeking strategies to limit its greenhouse emissions with the aim of peaking around 2030 at the equivalent of about 65 million tonnes of carbon dioxide [3]. Use of renewable resources such as biomass, wind and solar energy, can be one way to reduce the nation's electricity carbon foot print. Meanwhile, allowing entry of various energy options into the country electricity market, especially indigenous source, could diversify the fuel mix and reduce Singapore's dependency on imported fossil fuel.

2. Singapore waste management challenge

With the increase in population and affluence over the past decades, the amount of MSW generated each year keeps rising in Singapore. Fig. 2 shows the amount of disposed domestic, disposed industrial waste and waste recycled from year 2006 to 2015 [4]. In waste treatment hierarchy, the priority is given to waste material recycling. Singapore has been actively promoting waste minimization and recycling since the early 1990s [4]. The overall national recycling rate shows increasing tendency from 51% in 2006 to 61% in 2015, heading towards the target recycling rate of 70% by 2030. The remaining unrecycled waste is disposed either by incineration or landfill. Over the last 10 year, the total annual generation of MSW had increased steadily from 7.8 million tonnes in 2006–10.7 million tonnes in 2015 with an average annual increasing speed of 5%. However, owing to the upward changes in the recycling intensity, the annual growth in disposed waste was just 2% (Fig. 2) from 2.6 million tonnes in 2006–3.0 million tonnes in 2015.

The disposed MSW in Singapore can be classified into two major

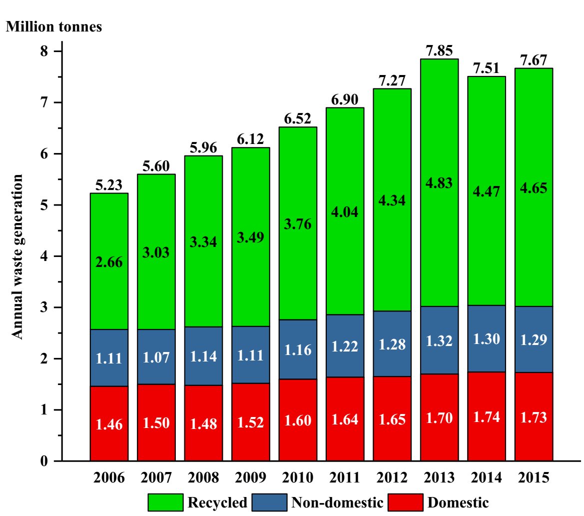

Fig. 2. Annual waste generation in Singapore. (Disposed waste refers to the remaining waste after recycling, which is the sum of non-domestic and domestic waste in this figure.).

categories: domestic and non-domestic refuse [5]. The first category refers to garbage collected from households, markets, food centres, hotels, restaurants, and shops, while the latter category is dominated by non-toxic and non-hazardous garbage from industrial premises and also contains small portion contributed by institutional facilities, such as government and statutory board installations, and public development projects. Based on the number of Singapore population including citizens and permanent residents, it was calculated that the disposed domestic waste per capita per day varied in the narrow range between 0.83 kg and 0.87 kg in the nearest eight years (Table S1). It was comparable with the data from the other developed cities, such as Tokyo (1.03 kg/capita/day), Seoul (1.08 kg/capita/day), and Berlin (0.88 kg/capita/day) [6], reiterating the find from Zhang et al. [7] that population growth alone was most probably the major cause of the growth of MSW in Singapore. By 2030, Singapore's total population escalates to range between 6.5 and 6.9 million [1]. Assuming no changes in waste generation per capita in the following year, the total disposed domestic waste could reach 5.4–6.0 million tonnes in 2030. The non-domestic waste generation is highly dependent on the economy growth [8]. A linear increment in GDP could be expected for Singapore's economic development (Fig. S1), while waste generation per dollar demonstrated a decline trend (Fig. S2) due to the increasing GDP share of Finance, Insurance and Business service, which produced less solid waste per dollar than traditional manufacturing and retail trade [9]. Assuming these patterns remained valid for the next fifteen years, the total disposed non-domestic waste was projected to be approximately 1.6 million tonnes in 2030. Overall, the domestic and non-domestic disposed waste was estimated to amount up to 7.3 million tonnes in 2030, which was more than double of that in 2015.

3. Seeking renewable energy from MSW

Singapore has continuously spent efforts on raising the contribution of renewable energy in the national energy mix to reduce dependency on imported fossil fuels. Renewable energy source includes solar energy, tidal energy and energy from biomass. Although they are unlikely to replace natural gas power plant to meet the high electricity demand, they can help to enhance energy resilience and environmental sustainability [10]. Among the renewable energy available, energy from waste is of great interest due to its ability to tackle waste management problem and yield sustainable energy addressing both concerns simultaneously. Energy from biogenic MSW, such as paper, cardboard, food waste, horticultural waste, wood, and animal manure, is considered as carbon-neutral and environmental friendly [11]. The carbon dioxide emission associated with biomass exploitation is commonly not assumed to contribute to global warming impacts, since the amount of CO_2 released during biomass utilization is offset by the CO_2 eliminated from the atmosphere by photosynthesis during the growth of biomass [12].

After waste generation, waste material recycling is preferred to energy recovery. The unrecycled waste is first considered for energy recovery by technologies other than incineration. The physico-chemical nature of the waste dictates the choice of the technology appropriate for treating such waste stream. Food waste, putrescible and high in water content (around 80% by weight), is suitable for anaerobic digestion [13]. Horticultural waste, with moisture content less than 45% and a calorific value in the range of 8 MJ/kg to 13 MJ/kg [14], is amenable for use as an alternative fuel for power and heat supply. Waste demolition wood featuring lower water content (i.e. 30%) could be converted to energy at a higher efficiency in gasifier. Waste plastic, consisting of polymers, is a favourable feedstock for pyrolysis to yield high calorific value fuel as well as petroleum refining comparable products [15].

This study reveals the current industrial practices in the field of waste-to-energy. This review focuses on various conversion technologies to summarize the current development stage, identify the encountered problems and foresee the future trends.

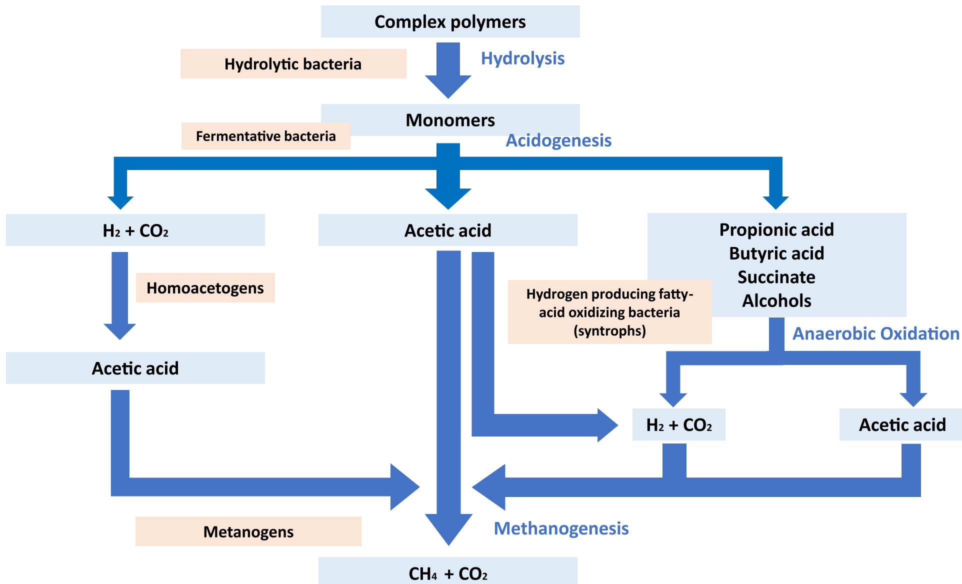

Fig. 3. Overview of the degradation pathway during anaerobic digestion. adapted from [17].

3.1. Anaerobic digestion

Anaerobic digestion (AD) is a microbial process to convert organic matter under oxygen free conditions into biogas, which mainly consists of methane (CH_4) and carbon dioxide (CO_2) with traces of other impurities, such as hydrogen sulphide (H_2S), ammonia (NH_3), and water vapour [16]. The transformation of complex high-molecular-weight organic compounds can be generally expressed by Eq. (1).

$$\text{Organic matter} \rightarrow CH_4 + CO_2 + H_2 + NH_3 + H_2S \quad (1)$$

As shown in Fig. 3, the bio-conversion of complex high-molecular-weight organic compounds into biogas is the result of complex interactions among different microorganisms: (1) fermentative bacteria, (2) hydrogen-producing acetogenic bacteria, (3) hydrogen-consuming acetogenic bacteria, (4) carbon dioxide-reducing methanogens, and (5) acetoclastic methanogens [17]. The digestion process may be subdivided into four steps: (1) hydrolysis; (2) acidogenesis; (3) acetogenesis; and (4) methanogenesis [18].

Due to the capability of reducing chemical oxygen demand (COD) and biological oxygen demand (BOD) from waste streams and producing renewable energy, AD processes have successfully implemented in the treatment of livestock and agricultural wastes, food waste (FW) and wastewater sludge [19].

3.1.1. Digestion of FW in Singapore

FW generation is a growing concern in Singapore. In 2015, Singapore generated 785,500 t of FW, which was about 0.39 kg per person per day and accounted for about 10% of the total waste generated [4]. With only 13% being recycled, the rest were disposed of at the waste-to-energy plants (Table S2). The amount of FW generated has increased by around 40% over the past 10 years, and is expected to further increase with a growing population (Table S3). Besides the resources needed to collect and dispose it, FW contaminates recyclables, compromises recycling efforts, and causes odour nuisance and vermin proliferation if not managed properly [20]. The National Environment Agency (NEA) of Singapore has thus come up with FW management strategies as shown in Fig. 4 [21]. Reduction of food wastage is at the top of the hierarchy, followed by the redistribution of unsold and excess food. When FW generation is unavoidable, the next strategy is to recycle FW, such as through AD into biogas and through composting into soil conditioner. The burning of FW in waste-to-energy plants is the least preferred way of managing food waste.

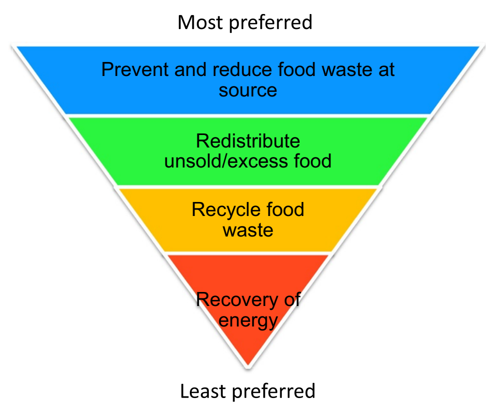

Fig. 4. Food waste management hierarchy in Singapore, adapted from [21].

While reducing FW might be the most preferred solution, recycling and treatment of unavoidable food waste are just as crucial. In the year 2005, the first FW recycling company, IUT Global Pte. Ltd. was set up in Singapore. The recycling company adopted the AD method combined with composting. The FW recycling process by IUT Global was launched in two phases [22]. Phase I, operated since 2007, had an installed capacity of 3.5 MW power and could treat 300 t of food waste per day. Phase II was planned to come into commission since 2009 and would be able to treat 500 t of food waste per day with an installed capacity of 6 MW power.

IUT collected FW from various localities around Singapore, including hawker centres, food courts, hotel, restaurants, and other commercial and industrial food establishments. In its designing of Phase I, 300 t of FW were delivered to the plant and fed into a bag breaker to release the bagged waste. The following screener could reject the large piece of plastic and non-biodegradable materials, such as glass bottle and metal can. Thereafter, the anaerobic digestion of organic slurry (ADOS) mill, a patented wet mill of IUT, was employed to reduce the particle size of the waste. The slurry with the addition of extra water leaving the ADOS mill was moved to the sedimentation tank, in which 3 layers were formed. The floating layer (mainly containing plastic) and the bottom layer (including glass, metal and heavy bones) were sent to the nearest incineration plant. The rejected impurity was estimated to be 11% of the incoming FW by weight. The middle layer with the highest content of putrescible material was pumped to the anaerobic

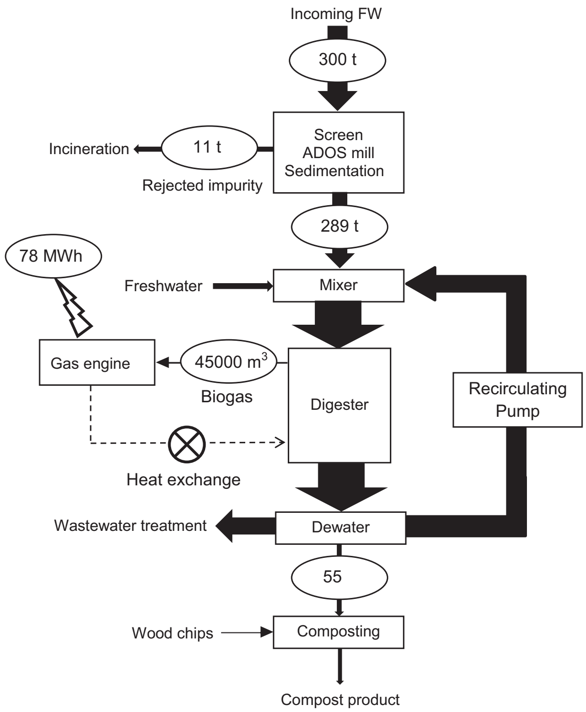

Fig. 5. Process flow of IUT food waste digestion process.

digester for an average 21-day thermophilic (52–55 °C) fermentation. The main product, 45,000 m^3 biogas with 60–64% of methane was combusted in a Combined Heat & Power (CHP) unit to generate bio-power of 78 MWh per day. Excluding 1.2% internal consumption of the plant, the net power sold to the national grid took up 98.8% of the total electricity produced. Heat recovered from CHP unit was channelled to the digester to help maintain the thermophilic condition. The digestion residue passed through a dewatering system, after which majority of the liquid fraction was reused on-site and certain aliquot was treated in situ before draining into the sewer system. Fifty-five tonnes of the de-watered digestate with water content around 74% was co-composted with wood chips for an average of 28-day maturation treatment [23]. The yielded compost product was commercially sold as topsoil or soil amendment for landscaping, if the quality of the product met the local standard for compost (Table S4). The flow diagram for IUT FW process is presented in Fig. 5.

Unfortunately, in 2010, IUT Global suspended the plans for Phase II and ended their business in 2011 after it was unable to procure sufficient FW to sustain the operational costs of the recycling plant. By March 2011, IUT Global managed to collect only 120–130 t FW per day. Among the FW collected, up to 40% of FW collected was sullied with plastic bags and other inorganic trash, which had to be sent for incineration, raising operation costs [22].

Due to the closure of Singapore's largest FW recycler, IUT Global's customers (such as hotels, cafeterias, food manufacturers and markets) had to look for alternative recycling services, while others resorted to incinerating their waste. The small number of FW recyclers has increased over the years, including Eco-Wiz and VRM BioLogik. The ecoDigester at Ang Mo Kio Block 628 Market (neighbourhood market and food centre) supplied by Eco-Wiz is able to decompose one tonne of FW daily with the help of microbial additives at the optimized level of aeration, moisture and temperature [24]. The water contained in the FW is collected and purified for site cleaning. Although each unit costs up to $110,000 up front, users can save on incineration fees. The machine at Tiong Bahru Market (neighbourhood market and food centre in central Singapore), under VRM BioLogik, grinds up FW and inoculates it with cyanobacteria and other microbes [25], which together could break down organic substrate into amino acid, and low-molecular polysaccharides. The resulting liquid products are sold as bio-fertiliser for agricultural purposes.

3.1.2. Digestion of sewage sludge in Singapore

A large amount of sewage sludge is generated during the activated sludge water treatment process. Cost for the treatment and disposal of sewage sludge may take as high as 50% of the total cost for a wastewater treatment plant [26]. Anaerobic digestion is commonly considered as a promising way to treat sewage sludge since it can remove odours and pathogens, stabilize sludge and produce green power through biogas [27].

There are currently four wastewater treatment plants (WTTPs) in Singapore to handle 100% of the used water from both the domestic and non-domestic sectors. In 2015, 574.8 Million m^3 of wastewater was treated to standards fit for discharge into the sea [28]. Briefly, in WTTPs the wastewater underwent primary settling, aerobic biodegradation and secondary sedimentation before discharging. Based on the interviews with an official from PUB (Singapore's National Water Agency), it was found that 0.078 kg of dry primary sludge and 0.032 kg of dry activated sludge were generated per cubic meter of treated wastewater [29]. The produced sludge was thickened (from 0.4% to 4.0% total solids) followed by AD, where around 45% of the VS was decomposed and 0.80 m^3 of biogas (64% CH_4) was produced per kg degraded VS [30]. The biogas was then used as fuel to power dual-fuel engine generators which could cover 20–30% of the electrical energy required at the plant.

3.1.3. Co-digestion of sewage sludge and FW

Anaerobic co-digestion of sewage sludge and FW showed higher methane yield compared to when sewage and FW in non-mixture conditions, and the process is kinetically much faster than sole digestion, because co-digestion allows the utilization of the nutrients and microbes in both substrate to optimise the digestion process and takes the advantage of synergistic effect of microorganisms [31].

The first co-digestion plant in Singapore was established in 2015 by PUB and Anaergia Pte Ltd during the Singapore International Water Week Technology and Innovation Summit. As the technology is in its testing phase, the demonstration plant could treat only up to 40 t per day of combined used water sludge from the Ulu Pandan Water Reclamation Plant (WTTP in western Singapore) and source-segregated FW collected from an upcoming food-waste recycling pilot in a nearby district. FW is currently being collected from a number of premises including schools, army camps as well as a food court. NEA plans to progressively expand the pilot to more suitable premises. The operation of the co-digestion facility is still on-going and its successful operation would facilitate similar processes being implemented at future co-located Integrated Waste Management Facility (IWMF) and PUB's Tuas Water Reclamation Plant (TWRP), which is able to take 400 t of FW for co-digestion [32].

3.1.4. Assessment of AD status and potential in Singapore

In Singapore, AD has been extensively used to recover energy from sewage sludge while the low recycling rate is observed for FW, animal manure and brown water (BW: faeces-without-urine), where larger biogas potential is embedded.

According to 2015 statistics, out of 785,500 t of FW, only 104,100 t are recycled into animal feed or soil fertilizer. The other 681,400 t were burnt in IPs and produced 82.7 GWh electricity (Eq. (2)), among which 64.5 GWh were exported to national grid considering 22% internal power consumption by IPs. However, incineration of FW is considered as energy intensive due to its high moisture content, because incinerators lose significant energy to vaporise the water content before the energy potential of the FW is realized for the ultimate power generation. If source separation was conducted and the unrecycled FW was directed to AD plant, 39,923,226 m^3 CH_4 (Eq. (3)) could be harnessed

Table 1
Parameters used for calculating waste energy potential.

Item	Value	Source
Food waste digestion		
Food waste element	46.3% C, 7.0% H, 3.3% N, 0.2% S, 22.2% O, 21% Ash	[33]
VS in wet mass	18%	[33]
Food waste moisture	77%	[33]
Methane generation potential	465 m^3/t VS	[33]
LHV	2.3 MJ/kg wet mass	[33]
Animal manure digestion		
Chicken manure property	29.56% TS, 19.82% VS in wet mass	[34]
Chicken manure element	28.2% C, 3.6% H, 3.5% N, 1.09% S,16.7% O, 46.9% Ash	[35]
Methane generation potential	278 m^3/t VS	[34]
Chicken manure LHV[a]	1.6 MJ/kg wet mass	
Horse manure property	24.7% TS, 18.1% VS in wet mass	[36]
Horse manure element%	37.3% C, 5.1% H, 2.0% N, 0.5% S,28.1% O, 27% Ash	[36]
Methane generation potential	340 m^3/t VS	[36]
Horse manure LHV[a]	2.0 MJ/kg wet mass	
Brown water digestion		
VS in wet mass	1.9%	[37]
Methane generation potential	280 m^3/t VS_{add}	[37]
Wood as fuel in CHP plant		
Wood chips LHV	14.4 MJ/kg wet mass	[38]
Electric efficiency in CHP plant	25%	[39]
Thermal efficiency in CHP plant	55%	[39]
Electric consumption in CHP plant	110 kWh/tonne	[40]

[a] LHV is calculated based on the following equations: HHV = $0.35X_C + 1.18X_H + 0.10X_S - 0.02X_N - 0.10X_O - 0.02X_{ash}$, LHV = HHV(1-M%)-2.447 M %,where X is the mass fractions (percent mass dry basis) for Carbon (C), Hydrogen (H), Sulphur (S), Nitrogen (N), Oxygen (O), ash content (ash), and M is the wet basis moisture content (mass fraction decimal).

during AD based on the data in Table 1. If methane energy content of 36 MJ/m^3 and engine electrical conversion efficiency of 40% [41] were considered, 137.9 GWh of electricity could be exported to the grid (Eq. (3)) excluding 32 kWh per tonne FW of internal usage in AD plant [23].

$$EI = Mass \times LHV \times EF_{inc} \tag{2}$$

where, EI: electricity produced from incineration (kWh); Mass: total amount of biomass (kg); LHV: low heating value of wet mass (MJ/kg); EF_{inc}: electricity conversion efficiency of IPs, 19%.

$$ED = Mass \times VS \times ME \times HV \times EF \times 0.7 \tag{3}$$

where, ED: electricity produced from digestion (kWh); Mass: total amount of biomass (kg); VS: volatile solid percentage in wet mass; ME: yield of methane per volatile solid fed m^3/kg; HV: methane heating value, 36 MJ/m^3; EF: electricity conversion efficiency of biogas engine, 40%; 0.7: the realistic output coefficient, as the real AD plant can seldom reach 100% of the methane yield like that under laboratory condition [42].

Singapore currently has three chicken farms, each of which has more than half a million hens for producing eggs and is planned to increase the number to 1.3–1.5 million chickens by 2025 to decrease the dependency on imported eggs [43]. Assuming each chicken producing approximately 100 g of manure daily [44], at least 60,000 t per year of CM was produced currently, which could generate 2,314,183 m^3 CH_4 during AD based on the data in Table 1. Horse manure (HM) is a mixture of faeces and bedding materials (straw, woodchips, etc.) and is one of the major sources of animal manure in Singapore. It is estimated that around 30–40 t of HM were produced from Singapore Turf Club every day [36]. Taking 550,321 m^3 CH_4 generated from AD of HM into account, around 9.1 GWh of biopower was embedded in Singapore animal manure.

Among wastes generated within the household, FW has the highest organic content, followed by brown water. Recent researches showed that BW was suitable as substrates for the anaerobic digestion process to recover biogas [45,46]. Based on Ng's investigation, 4 L water was needed to flush faeces (0.15 kg) into the sewage system per capita per day [29]. Given that 0.576 kWh of energy was required to remove 1 kg of COD [30], 3.45 kWh was consumed in WTTPs for purifying BW (4.1 g COD/L) per person annually, which indicated that Singapore utilized 19.1 GWh of electricity to treat human excrete in 2015 (5.54 million of population). If BW could be separately collected through the no-mix toilet and fed into the digester, 30,121,202 m^3 CH_4 would be produced and provide 120.5 GWh of power to the grid, in addition to saving 19.1 GWh in WTTPs.

Table 2
Comparison of electricity output between current situation and proposed AD scenario for current unrecycled waste (Unit: GWh).

Waste stream	Current scenario	Proposed scenario
Food waste	64.5	137.9
Brown water	−19.1	120.5
Animal manure	5.3	9.1
Sum	50.7	267.5

As shown in Table 2, the proposed AD scenario led to 267.5 GWh of electricity output, which is fivefold of the current situation (50.7 GWh) and can meet another 0.5% more of national electricity demand. The largest power potential was found in FW, presenting 52% of the total electric capability newly identified. The calculation related to AD assumed that all the substrate was digested alone without other biodegradable material as co-substrate. This was conservative and the electricity generation could be much higher if co-digestion was modelled, as it had been found that methane yield can be significantly increased by the synergy between different feedstock [31,41]. It was also worth mentioning that the above calculation only concerned electricity production and did not take harnessing waste heat into consideration. Combined heat and power (CHP) generation or tri-generation plant further doubles the energy efficiency, which is illustrated in Section 3.2.

After digestion, there is still a considerable amount of organic matters (digestate) left in the residue, which contains both undegraded and nondegradable organic compounds as well as nutrients. An additional aerobic treatment step can convert the organic residues into biocompost as a substitute for synthetic NPK fertilizers [47]. On top of the other more obvious benefits of AD (energy recovery and reduction of GW impacts), this not only eliminates sending residue into landfill (such as bottom ash in IPs), but also contributes to the reduction in acidification and eutrophication impacts during waste management [20,48].

3.2. *Combined heat and power generation from biomass firing*

Combustion-based CHP, also known as co-generation, refers to the thermodynamic process which simultaneously produces electricity and heat from biomass firing in the furnace [49]. Tri-generation is an extension to co-generation which involves the simultaneous production of electricity, heating and cooling in one conversion process [50]. Available biomass in MSW consists of agricultural by-products and residue, horticultural waste, manure, waste wood and sewage sludge.

In a standalone electric generating plant, steam, at high temperature and high pressure, is produced from the biomass-fired boiler and then injected into the steam turbine, causing the turbine to rotate and produce electricity. In condensing steam turbine, the electrical efficiency is maximized by cooling the exhaust steam (at the low-pressure and low-temperature stage) from the main turbine into a condensed state at a pressure well below atmospheric. This provides a vacuum at the exit side of the turbine and increases the pressure drop across the blade, which results in greater energy extracted from the steam and higher electricity output for a given amount of steam [51]. The efficiency of

fuel conversion to power is 30–40% from condensing turbines in typical centralized biomass power plants [52], and the remaining 2/3 part of the energy content of the fuel is typically wasted as heat in the flue gases of steam boiler and the cooling water of condenser.

A cogeneration system recovers the heat rejection in the condensation process for use in heating, cooling, dehumidification or for steam generation. By capturing and using waste heat, the utilization rate of the fuel energy can be significantly improved, ranging from 70% to more than 90% [50]. There are two major types of steam turbines employed in CHP plant, depending upon the exit pressure of the steam: extraction condensing turbine and backpressure turbine [53]. The extraction condensing turbine is a variation of a straight condensing turbine. It also exhausts steam at a pressure well below atmospheric, but with design to allow steam to be withdrawn from various stages of the turbine, which has the advantage of being able to adjust the heat and power generation levels to different requirements. Biomass CHP plants relying on condensing turbine have electrical efficiencies from 22% to 28%, while total thermal efficiencies are over 80% [39]. Backpressure turbine works without condensation and discharges steam with an exit pressure of at least equal to atmospheric pressure. The extraction of steam at the intermediate pressure from the turbine results in a decrease in shaft power, and then lowers the electrical efficiency. However, it has a high thermal efficiency, since it does not reject heat in the condensation process. This turbine, which is simple and inexpensive, is suitable for some sites with a constant steam demand of intermediate pressure, such as palm oil mill [54] and sugar mill [55]. For biomass CHP plant relying on backpressure turbine, electrical efficiencies between 10% and 20% and total efficiencies between 80% and 90% are reported [39].

The typical size of biomass CHP plants is ten times smaller (from 1 to100 MW) than coal-fired plants due to the low availability of local feedstock and high transportation cost resulted from low bulk density and low energy density of biomass [52]. The key factor affecting the business success of biomass CHP is the thermal utilization ratio. To achieve a reasonable financial payback, it is necessary to ensure more than 60% of the available thermal energy from the turbine to be used on an annual basis unless the project is motivated by other purpose (such as mainly functioning as waste disposal facility). Therefore, biomass CHP plant is particularly suitable for sites, which have a simultaneous and constant need for electric power and thermal energy over long operating hours, such as industrial premises and hospitals [56].

3.2.1. Existing biomass CHP practice in Singapore

Currently, the only urban biomasses utilized in CHP system are waste wood and horticultural waste, which could be collected from unwanted pallets, crates, boxes, furniture and wood planks used in construction, as well as tree trunks and branches generated during the pruning of trees and plants all over Singapore. In 2015, there were 362,000 t of horticultural waste and 370,600 t of waste wood generated, among which 278,000 t were used as feedstock in biomass power plants and 252,900 t were converted into compost and new wood products, resulting in a total recycling rate of 79% for waste wood and 66% for horticultural waste (Table S2). Until now there are two co-/tri-generation biomass plants in Singapore, all managed and operated by a Singapore-based company Ecowise group. The two projects are tri-generation Energy Resource Centre at Gardens by the Bay and co-generation biomass power plant at Sungei Kadut.

A waterfront nature park spanning 101 ha green areas in central Singapore, Gardens by the Bay accommodates the Cloud Forest and Flower Dome conservatories, which house plants and flowers from the cool-moist tropical montane and cool-dry Mediterranean regions. The Energy Resource Centre within the garden is built under the Public-Private-Partnership (PPP) initiative by Ministry of Finance (MOF), and the detailed schematic diagram is shown in Fig. 6. Since opening in 2011, the horticultural waste from tree cutting and wood waste collected from other areas in Singapore are processed off-site and feed into in situ furnace to generate 9.5 t steam per hour. The steam drives the turbine to output 0.93 MW electricity to Gardens by the Bay's power grid. The waste heat recovered from the turbine is utilized to regenerate the liquid desiccant for removing air moisture from the conservatory, which provides a dry atmosphere mimicking a temperate climate in Flower Dome. The heat is also used in 2 units of absorption chillers to produce a cooling load of 675 kW. Exhaust gas from biomass furnace is purified by cyclones and electrostatic precipitators, and then vented through 25–50 m tall Supertrees, which is the iconic tree-like structure and covered with living plants growing on the artificial trunks. The ash leftovers from the furnace are utilized as soil amendments as well as fertilizers on site [57].

The CHP plant located at Sungei Kadut (industrial estate and planning area in north Singapore), operating since 2004, has an electrical capacity up to 1 MW and steam production capacity of 15 t/h by burning horticultural waste and wood waste. The generated electricity ensures the plant self-efficiency for operating electrical facilities such as sorting and crushing machines, while the waste steam is used on-site in several industrial applications such as drying wet spent barley grains and wet soya beans to produce animal feeds as well as heating ISO-tankers containing chemical additives [58].

There is a third biomass boiler in the Sakra area of Jurong Island (energy and chemicals industrial estate located to the southwest of the main island of Singapore) under Sembcorp. It has been in commission since 2011 with a steam production capacity of 20 t per hour, which was expanded to 60 t per hour in 2013. It could convert 400 t woodchip daily processed from construction and demolition waste collected by Sembcorp's solid waste management operations to steam for nearby petrochemical manufacturers' demanding [59]. This plant cannot be classified as CHP system, since the product is steam only. However, given that it is still classified as combustion based biomass-to-energy practice; it is mentioned under this category.

3.2.2. Future planning in biomass CHP application in Singapore

Singapore is planning a sludge fluidised bed (FB) combustion system as part of the IWMF. When completed in 2027, this system can treat 800 t/d of dewatered digested sludge from the TWRP in the FB boiler. The produced power is supplied to the national grid, while the steam is consumed during sludge thermal hydrolysis in the digester and greasy waste treatment in TWRP [60]. Compared with grate furnace, FB boiler enables nearly complete combustion and is identified as the best technology used to burn a fuel such as sludge with low quality, high ash content and low calorific value [61]. The high performance of burning is realized through an intimate mixing among fuel, air and inert bed material (e.g. sand) with good heat conducting ability in a turbulent motion by an upward moving fluidizing air [62].

3.2.3. Assessment of biomass CHP status in Singapore

Combustion of biomass for energy has been practiced since man discovered fire and the technologies developed today enable almost full energy recovery efficiency. In 2015, 76,900 t of wood was disposed in IPs, contributing 45.6 GWh to Singapore electricity market based on the assumption made on Table 1. If these woods could be fuelled into biomass CHP plant, 76.9 GWh of electricity and 169.2 GWh of thermal energy could be harvested. Assuming that 110 kWh/tonne electricity was consumed for operating the boiler [63], the output electricity (68.4 GWh) was enough to satisfy the annual energy requirement of five thousand more households than incineration, considering a monthly power consumption of 400 kWh for 4-room Singapore household. According to Ecoinvent V3.3 database, 0.064 kg CO_2eq was emitted for generating 1 kWh of electricity from wood CHP system [38]. The annual electricity export of 68.4 GWh could result in a net avoidance of 28,766 t CO_2eq because of the substitution of the equal quantity of Singapore grid electricity (As mentioned in Sections 1, 1 kWh of Singapore grid electricity had a global warming impact of 0.48455 CO_2eq).

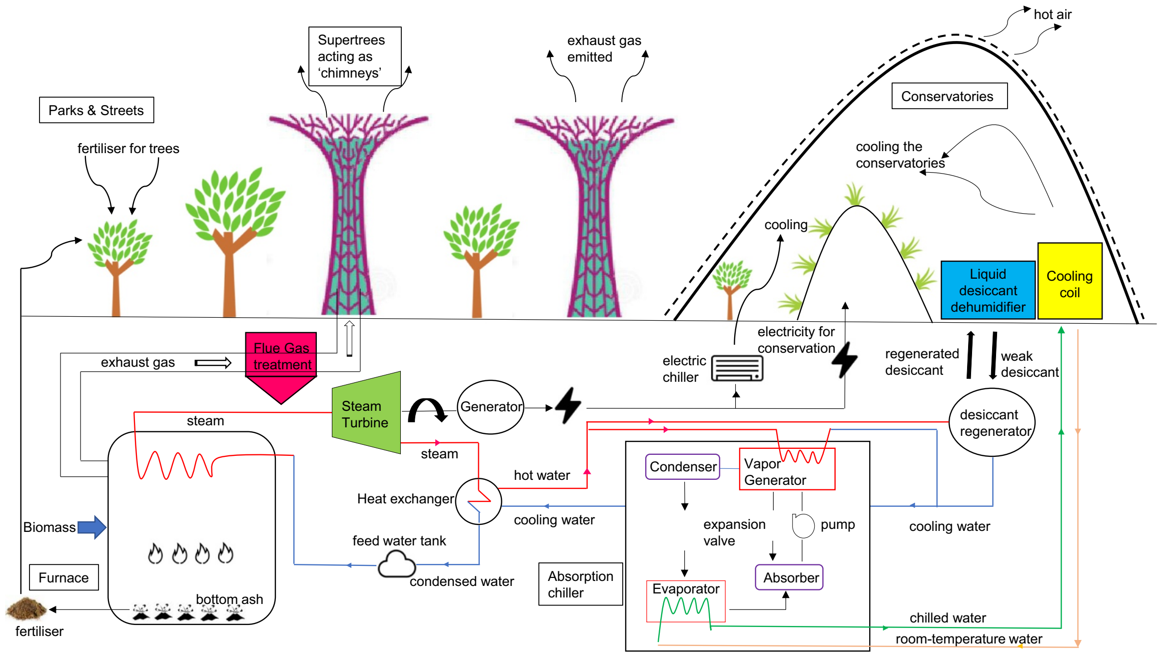

Fig. 6. Schematic diagram of the tri-generation plant @ Gardens By The Bay.

Since high thermal utilization is critical to achieving the maximized efficiency and financial outcome, a local and stable heat or cooling demand must be ensured during the planning of the CHP scheme. Potential steam off-takers may include plants at the biomedical park in Tuas and the silicon wafer parks in Woodlands and Tampines [43].

3.3. Gasification

Different from the combustion process during which solid fuel is burned with the supply of excessive amount of air (or O_2), in gasification conversion solid waste reacts with little or no oxygen, breaking down the feedstock into smaller molecules and converting them into syngas (mainly consisting of CO_2, H_2, CO, and CH_4). Gasifiers have been classified into four different categories based on the sequence of reactions, gasifying agents, and stream configurations [64]: (i) Fixed-bed reactor, which includes updraft gasifier and downdraft gasifier, (ii) Fluidized bed reactor, which includes the bubbling fluidized bed and the circulating fluidized bed reactor, (iii) Entrained flow reactor. The sequence of reactions for solid and gas species within the gasifier differs for different reactor types. Fig. 7 shows the schematics of the commonly used gasifiers in the market today.

3.3.1. Gasifier types

3.3.1.1. Fixed-bed gasifier. Fixed bed reactors are also called moving beds, due to the slow motion of the solid feedstock with respect to the gasifying agent [65]. Two types of fixed-bed gasification reactors are illustrated in Fig. 7(a) and (b): updraft (counter-current) and downdraft (co-current) reactors. Updraft gasifier is able to handle solid feedstock with moisture contents as high as 50% [65]. However, because of the low exit temperature, tar content is usually high in the producer syngas. In a downdraft gasifier, syngas exits from the bottom of the reactor at relatively high temperature. As syngas passes through the high-temperature reduction zone, a considerable amount of energy is drawn, which leads to the reduction of thermal efficiency [66]. However, the high temperature also aids in the consumption of tar [65]. Therefore, downdraft gasifier is preferred for small-scale power generation due to lower tar content in the producer gas.

3.3.1.2. Fluidized bed gasifier. In fluidized bed gasifiers, the feedstock is continuously fed close to the bottom, while the gasifying agent enters from the bottom. Fluidized bed gasifiers are able to handle high throughput, however, their application is limited due to low carbon conversion [66]. In a fluidized bed, there is a better distribution of feedstock and the fluidization effect reduces heat and mass transfer limitation, leading to an increase in the heating value of producer gases and energy efficiency [67]. However, more particulates in the producer gas exist as a result [68]. There are two types of fluidized bed: bubbling fluidized bed (Fig. 7(c)) and a circulating fluidized bed (Fig. 7(d)).

In a bubbling fluidized gasifier, gasifying agent flows in the reactor chamber at the minimum fluidizing velocity and the reactor operates in a similar manner to a general fluidized bed reactor. The circulating fluidized gasifier adds an extra dimension to the process, re-circulating solid fuels back to the reaction vessel through an attached cyclone separator. Since it could be operated at very high gas velocity and a large amount of solid fuels could be recycled in the process, circulating fluidized bed could handle high throughput [69]. It has higher thermal efficiency compared to bubbling fluidized reactor because there is no bubble existing in the reactor chamber [65].

3.3.1.3. Entrained flow gasifier. In entrained flow gasifiers, both the fuel powders (usually less than 75 µm) and gasifying agents enter through the top of the reactor, as shown in Fig. 7(e). The gasifying agents flow in at high velocity to entrain all the fuel particles. Usually the entrained flow gasifier reactor could be operated at a temperature between 1200 °C and 1600 °C [69]. Therefore, this type of gasifier could reach high carbon conversion and low tar content in the producer syngas. However, the fuel particle size is required to be small enough to be entrained. To achieve small fuel particle size, grinding sometimes is challenging. In addition, effective cooling equipment is needed for the post-treatment of hot syngas.

Despite the wide range of different gasifiers available in the market, some gasifiers are more commonly used than others. The popular gasifier types include downdraft (75%), fluidized bed (20%) and updraft (2.5%), with the remaining 2.5% being made up with all other types [70].

3.3.2. Gasification reactions

The fixed-bed downdraft gasifier is usually characterized into four different zones and their respective reactions have evolved extensively as a result of the intensive studies conducted on this type of gasifiers

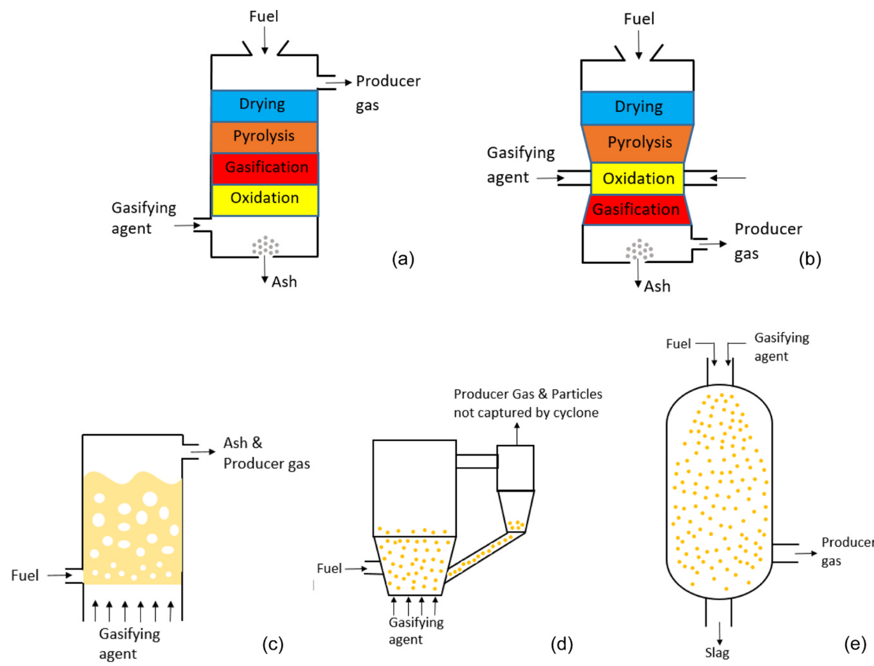

Fig. 7. Commonly used gasifiers (a) Updraft Fixed-bed Gasifier; (b) Downdraft Fixed-bed Gasifier; (c) Bubbling Bed Gasifier; (d) Circulating Fluidized Bed Gasifier; and (e) Entrained Flow Gasifier.

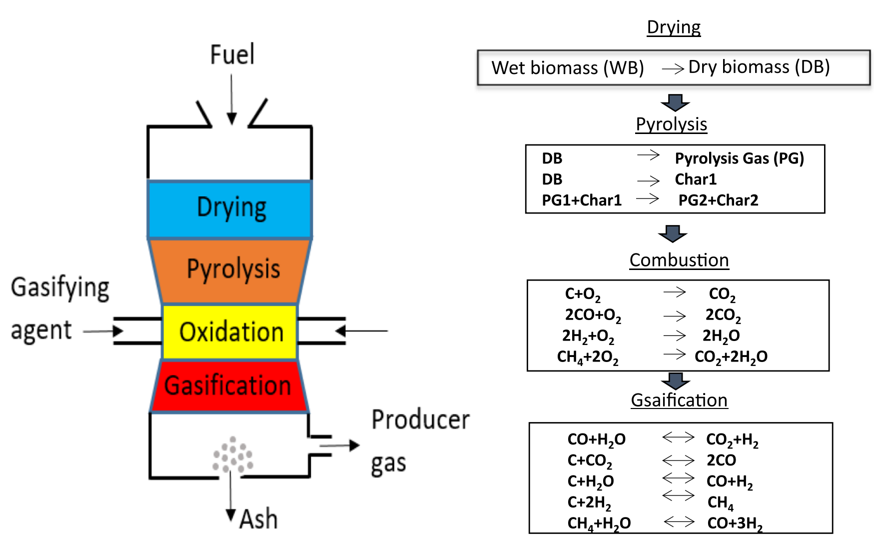

Fig. 8. 4-zone modelling concept and all the main gasification reactions.

since the early 1930s [71]. Di Blasi [72] first proposed a complex network of reaction equations that were classified into the different gasification stages of (i) drying (ii) pyrolysis (iii) combustion and (iv) gasification (reduction), with outputs encompassing time-based axial gas composition and temperature profiles. Later on, several researchers developed similar approaches to simulate syngas composition considering single one stage (only reduction zone) or multi-stages of the process [73–77]. These approaches vary in several aspects, ranging from different reactor configurations to reaction kinetics with different degrees of compliance [78]. The 4-zone modelling concept and all the main gasification reactions are shown in Fig. 8. The first stage is drying, which involves the process of drying out moisture content within the biomass particles. In the pyrolysis zone, biomass particles are heated up to 700 °C to be converted to char and release volatiles. Meanwhile, tar is also produced in this stage. The third stage is combustion. Char and volatiles undergo exothermic reactions with oxygen to produce heat and gaseous mixture (H_2O, CO_2, and CO). The final stage is gasification, where char and tar react with the gasifying agent (CO_2 and H_2O) to produce syngas, which mainly consists of CO, H_2 and CH_4. These reactions are endothermic and require heat input from prior combustion reactions.

3.3.3. *Current gasification status in Singapore*

In Singapore, there have been some research investigations on pilot-scale and lab-scale gasification technology. In National University of Singapore (NUS), Chi-Hwa Wang's group has conducted experimental and numerical studies on pilot scale downdraft gasifier (10 kg/h). Efforts have also been spent on reutilizing produced biochar into commercial products such as catalyst and activated carbon. In addition, some industrial gasification facilities are under construction. Different scales of the integrated system (i.e. 1 MW industrial scale from BioPlas Energy (Asia Pacific) Pte Ltd) are being developed in Neo Tiew industrial plant. Test bedding gasification of sludge is performed in collaboration with Sembcorp industries Ltd to analyse the cost-benefit

Table 3
Syngas composition of co-gasification of wood chips and solid waste.

Feedstock	wt%[a]	CO vol%	CO_2	CH_4	H_2	O_2	Syngas $CO+H_2$	LHV MJ/Nm^3
Wood Chips	100	15.05	15.64	4.68	16.59	0.15	31.64	4.68
Food Waste	20	21.44	12.24	5.52	19.48	0.06	40.92	5.52
Food Waste	30	21.42	10.60	5.22	17.63	0.11	39.06	5.22
Food Waste	40	22.63	11.77	5.17	17.02	0.08	39.66	5.17
Chicken Manure	30	20.34	11.79	5.23	17.70	0.32	38.03	5.23
Horse Manure	30	19.55	14.46	5.57	19.70	0.09	39.25	5.57
Sewage Sludge	10	15.90	12.20	4.61	17.10	1.70	33.00	4.61
Sewage Sludge	20	15.60	12.70	4.51	16.80	1.00	32.40	4.51
Sewage Sludge	30	12.00	21.50	3.60	13.40	3.85	25.40	3.60

[a] Weight percentage of solid waste in the feedstock during co-gasification of wood chips.

analysis for both gasification and the existing incineration. Nanyang Technological University (NTU) is undertaking joint research project "Development of Enhanced Utilization Methodologies for Slagging Gasification" with JFE Engineering Corporation. The slagging gasification plant locates in Tuas Industrial area and has the ability to handle 11.5 t of MSW per day. The construction of the facility is projected to be completed by the end of 2018.

3.3.3.1. Experimental and numerical study on gasifier reactor. Wang's group used different kinds of solid waste as feedstock for gasification experiment, including wood chips, FW, HM, chicken manure and sewage sludge [73,79]. Table 3 lists the property of syngas produced from various mixing ratio of solid waste with wood chips. By comparing the compositions of producer syngas generated from the different feedstock, it is found that the ash content, C/H/O content and structure in solid waste affect low heating value (LHV) of the produced syngas. In addition, the LHV of syngas from co-gasification of horse manure (30%) was increased by 19% compared with pure wood chips. Meanwhile, challenges were encountered with the diversified feedstock. For example, the high Fe in sludge (30%) and the high fraction of small particle in FW (40%) resulted in blockage in the gasifier.

Some attempts have also been made to develop a hybrid waste treatment process which combines AD and gasification for energy recovery from lignocellulosic biomass waste [80,81]. At the first stage, AD of lignocellulosic biomass waste is conducted by mixing with anaerobic sludge. At the second stage, co-gasification is added as post-treatment for the AD residue to produce syngas. The feasibility of the proposed two-stage hybrid system is validated experimentally and numerically and it is found that the proposed hybrid system could effectively improve the quality of produced gas.

Furthermore, the numerical study has also been conducted to provide researchers with an efficient tool for the prediction and optimization of the energy performance and economics of the gasification system [82–85]. Computational fluid dynamics (CFD) modelling has been conducted to investigate the reactor geometry (i.e. reactor probe position) and solid-solid mixing behaviour on downdraft gasification performance. Energy efficiency and syngas composition are analysed by feeding different gasifying agents (i.e. CO_2 and air) into the fluidized gasifier through CFD modelling. A 1-D kinetics model is also developed together with a graphical user interface (GUI) as a cost-effective tool to predict energy performance of a downdraft gasifier.

3.3.3.2. Re-utilization of gasification residue. Although gasification residue is not classified as a toxic waste, it may contain various compounds such as metal oxides, hydroxides and alkali salts. Improper disposal of bottom ash wastes may cause all types of pollution i.e. air, soil, and water. Toxicity assessment has been conducted on the bottom ash. It is found that the bottom ash extract has a high basicity and a high ionic strength, due to the presence of alkali and alkaline earth metals. Moreover, it also contains concentrations of heavy metals (e.g. Zn, Co, Cu, Fe, Mn, Ni and Mo) and non-toxic organic compounds [86]. In addition, the toxicity of gasification ashes is examined using *in vitro* and *in vivo* test methods. A standard protocol is established for the rapid screening of gasification ashes on the basis of *in vitro* and *in vivo* testing, which could guide the proper disposal of ashes [87].

Re-utilization of bottom ash seems to be a good alternative way for passive ash disposing. It not only offers a cost-effective and environmentally friendly way of recycling the ash, but also generates profit through the sale of materials that have a beneficial usage. After intensive examination, Wang's group proposes the following two recycling pathways:

1) Bottom ash can be converted into the active CaO catalyst because of the presence of high content of calcium compounds. The derived CaO catalysts are proved to exhibit high activity towards transesterification [88].
2) Char is a carbon-rich substance, which can be further mixed with soil and used for agriculture applications. It is found that water spinach grown in the soil-biochar mixtures grows better than that in pure soil or pure biochar, and water spinach grown in the 2:1 soil-biochar mixture shows the fastest normalized weekly growth rate [89]. Moreover, activated carbon derived from biochar of biomass gasification could be used for dye removal and exhibits high adsorption capability [90].

3.3.4. Future trend of gasification in Singapore

3.3.4.1. Solar steam gasification system. In industrial scale gasifier, a portion of the introduced feedstock is burned either directly (internal combustion) or indirectly (external combustion) with a controlled amount of air to supply heat for the endothermic gasification process. This practice not only lowers the feedstock utilization, but also contaminates the syngas with combustion products (e.g., CO_2, SO_x) [91]. To tackle the above-mentioned drawbacks, a research motivation is initiated by Wong's group in NUS to capture the solar energy as the process heat source for driving the gasification reaction. In Singapore, based on consideration of rain/cloud coverage and the highly urbanised landscape, the solar photovoltaic system can only effectively produce energy during an equivalent of 3.5 h or less in a day [43]. The proposed solar steam gasification system could store the day-time and variable solar thermal energy into syngas to allow for solar electricity production after sunset [92]. More importantly, integrating solar energy input with the gasification system could double the specific electric output, which is defined as the ratio of electric power output to the heating value of feedstock [92].

3.3.4.2. Integrated gasification system with tar reforming unit. The gasification technology has been existing for hundreds of years, but there are still some technical limitations related to gasifier design and syngas clean-up [93]. Tar formation is inevitable in the gasification process due to incomplete combustion of feedstocks. Tar is a sticky, complex mixture of aromatic hydrocarbons and may cause operational problems since some downstream processes, such as gas turbines may get clogged with the existence of cooled tar. Therefore, it is a critical challenge to realize tar removal in the gasification process. The catalytic reforming of tar is found to be an efficient way to remove tar from syngas. An integrated gasification and tar reforming system is under development by Wang's group in NUS to not only remove tar from the producer syngas, but also generate more syngas from the reforming reaction of tar.

3.3.5. Assessment of gasification status in Singapore

When wood chips were used as the feeding materials (moisture content: 8.2–8.5% by weight) by Ong et al. [73], the cold gas efficiency

(CGE) was calculated as 67% following Eq. (4). If the electrical efficiency of syngas engine was taken as 37.5% [94], the total electric conversion rate for the gasification power plant was 25%, which was comparable with biomass CHP plants relying on condensing turbine (22–28%).

$$CGE = Yield \times HHV_{syngas}/HHV_{feedstock} \tag{4}$$

where, Yield: Syngas yield ($m^3/kg_{feedstock}$); HHV_{syngas}: high heating value of syngas (MJ/m^3); $HHV_{feedstock}$: high heating value of feedstock ($MJ/kg_{feedstock}$).

Singapore gasification technique is still at an earlier stage of development, and much work is still needed before it can be commercialized as a sound option for exploiting energy from waste. The first barrier is the stable operation of the gasifier. The gasification plant control is more complex than combustion, as it is sensitive to numerous parameters, such as gasifying agents, gasifying agent-biomass ratio, air-fuel ratio, equivalent ratio, reaction temperature and pressure, which increase the chances of process failure [65]. Moreover, being non-well-mixed and inhomogeneous, the high variability of daily MSW may incur unwanted instabilities for gasification.

The second obstacle is gaseous pollutants in the produced syngas. For instance, tar condensation can cause clogging problems in downstream filters, heat exchangers, as well as gas mixing sections and inlet valves in the gas engine [93]. Other pollutants, such as benzene, may not affect the smooth running of the facilities, but presents toxic threats to human health [33].

Apart from burning in the gas engine to generate electricity, the syngas can be processed to a large number of products for various applications, such as methanol, dimethyl ether, formaldehyde and gasoline through Fischer-Tropsch reaction. The gasification residue can also be converted into valuable by-products, such as biochar. In addition to its benefits for plant growth, biochar can be considered as a carbon sequestration method, as the carbon in the biochar is stable and recalcitrant. In the life cycle analysis study by Ramachandran et al. [95], it was found that 33% of the credits for reducing greenhouse emission were realized by carbon fixation in biochar in the scenario of co-gasification of wood and sewage sludge.

3.4. Waste incineration

3.4.1. Introduction to incineration

Incineration involves burning the waste with the excess air supply to boil water to run the steam generator for electricity with/without heat as a co-product. This process not only realizes the volume reduction of solid waste up to 90%, which tremendously releases the demand on landfill space, but also recovers the energy embedded in the waste.

MSW is delivered into storage bunker by collection trucks before feeding into the incinerator. During storage, the generated bunker leachate is discharged from the bottom and the waste moisture is evaporated with the suction action of forced draught fan. The mixed, half-dry waste is then fed into the furnace by overhead grab cranes. The dominant MSW combustion technology is based on grate mass-burn, because of its simplicity and relatively low capital cost [96]. Proper design of the grate allows the optimized movement of waste through the combustion chamber and sufficient mixing of primary air drawn from the refused bunker with waste by means of revolving and agitating. The burning process runs at a high temperature of 800–900 °C, which also triggers the pyrolysis reaction and volatilizes partial organic component of the waste into combustible gases. Secondary combustion air and auxiliary fuel are supplied into the post-combustion chamber over the grate to ensure a complete burning of the gases as well as the proper breakdown of toxic organic substances (> 850 °C for 2 s) [97,98]. The hot flue gas then flows through the boiler to generate superheated steam (around 400 °C at a pressure of 40 bars), which is expanded in the turbine to produce electricity. The heat from the spent steam is further recovered in certain cases when there is a demand for thermal energy supply.

Leaving the steam boiler, the cooled flue gas (around 200 °C) is passed into air pollution control (APC) system for the removal of fly ashes, inorganic and organic gases, heavy metals, and dioxins to comply with legislative air emission standards [99]. Given the complexity of pollutants in the flue gas, the APC system comprises multiple stages, which usually begins with a multi-cyclone or electrostatic precipitator for dust control, followed by a wet or dry scrubbing system to neutralize and precipitate acid gases, such as HCl and SOx. The further abatement of heavy metals, dioxins, furans and VOCs are realized through active carbon adsorption or catalytic bag filter, with the latter system also fulfilling the function of NOx destruction. Besides, NOx mitigation is often dedicatedly performed by selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) [99]. The exact configuration of APC system varies from plant to plant, depending on the characteristics of the waste, incinerator type, local regulations, and financial support.

There are two generic ash streams discharged from the incinerators. Incineration bottom ash (IBA) consists of residues retained on the combustion grate and siftings that fall through the grate. Fly ash (FA) refers to the finer particulate matter collected from the combustion flue gas [100]. Reutilisation of bottom ash is a common practice in many countries, such as Denmark, the Netherlands and Germany, as the geotechnical properties and chemical ingredients of IBA resembles the light aggregates used in embankment and building construction [101,102]. By contrast, the dominant disposal method for FA is still landfilling, given that FA possesses a much higher hazardous potential resulting from its richness in certain heavy metal and dioxin [103].

3.4.2. Current incineration status of Singapore

In land scarce Singapore with only one constructed offshore landfill site available, incineration has been identified by NEA as the most preferred disposal way to treat the remaining incinerable wastes that are not recovered, reused or recycled. In 2015, about 38% of Singapore's waste was incinerated and another 61% was recycled, while the remaining 2% non-incinerable is landfilled (Table S3). On average, 7886 t of waste was incinerated daily and generated 3468 MWh electricity, 78% of which were exported to the national grid and made up around 2–3% of the Singapore total electricity consumption [4].

Table 4 lists the operation details of Singapore waste incineration plant (IP). The first IP of Singapore was commissioned at Ulu Pandan area in 1979 with a capacity of 1200 t/day, which was expanded to 1600 t/day in 1982 [5]. After 30 years of servicing period, it was phased out in 2009. There are currently five operating WTE plants in Singapore with two more in the pipeline. The Tuas IP which is owned by the government has been put into operation since 1987 with a capacity of 2000 t/day and a power output ability of 2 × 23 MW [104]. The Senoko IP has been in operation since 1992 with a design incineration capacity of 2400 t/day, and could offer an electricity supply up to 2 × 28 MW. It was privatised in 2009 with a 15-year Operation and Maintenance (O&M) contract to Keppel Seghers [105]. The Singapore largest IP is Tuas South IP, which is completed in 2000 with the ability to treat 3000 t waste daily and a power output capacity of 2 × 66 MW [106]. The Keppel Seghers Tuas IP is built and operated by Keppel Seghers under NEA's PPP initiative with its commission to dispose 800 t per day from 2009 to generate about 22 MW of green energy [105]. Unlike all the other IPs which exported electricity, Sembcorp IP generates steam as the sole product. Opened in 2016, Sembcorp IP is able to produce up to 140 t of 400 °C steam per hour for chemical and petrochemical companies on Jurong Island by processing 1000 t of industrial and commercial waste collected by Sembcorp's solid waste management operations daily [107].

The seventh plant (TuasOne IP) which can process 3600 t of waste daily is under construction by Hyflux Ltd and Mitsubishi Heavy Industries Ltd and is expected to be in commission at 2019 [108]. By that time, it can replace the Tuas IP, which is approaching towards the

Table 4
Operation details of Singapore MSW incineration plant.

Plant	Startup year	Capacity t/day	Turbine rated capacity MW	Gross electricity output kWh/t	Land occupation ha	Land capacity t/day/ha	Construction cost million
Ulu Pandan[a]	1979	1600	1 × 16	180	N.A.	N.A.	130
Tuas	1987	2000	2 × 23	350	6.3	270	200
Senoko	1992	2400	2 × 28	450	7.5	320	560
Tuas South	2000	3000	2 × 66	550	10.5	411	900
Keppel Seghers Tuas	2009	800	1 × 22	450[b]	1.6	500	450
Sembcorp	2016	1000	N.A	Steam	N.A	N.A.	250
TuasOne	2019	3600	120	800[c]	4.8	750	653
IWMF	2027	5800[d]	230	952[c]	68[e]	N.A.	3000[e]

[a] Phased out in 2009.
[b] Average electricity output per tonne of waste incinerated in current operating IPs.
[c] Estimated electricity generation.
[d] Apart from incinerating 5800 t of waste per day, IWMF also has the capability to process 400 t of food waste, 250 t of household recyclables and 800 t of sludge from the TWRP.
[e] Data refers to the total land occupation and total cost for IWMF and TWRP together.

end of its thirty year lifetime. The eighth incineration plant is part of IWMF, which is an integrated facility and aims to provide several solid waste treatment processes. Once it is in operation by 2027, IWMF could not only provide an incineration capacity of 5800 t/day to replace two older incineration plants (Tuas IP and Senoko IP), but also has the capability to process 400 t of FW, 250 t of household recyclables and 800 t of sludge from the TWRP [60].

Singapore IPs rely on grate incinerator to combust mixed MSW. Except for Ulu Pandan IP which employs a roller grate system [109], all the other electricity producing IPs use reciprocating grates. This grate design comprises the fixed and reciprocation steps in a sequence. In Keppel Seghers Tuas IP, these reciprocating steps move forward and backwards horizontally to push the refuse layer on the grate forward. Tumbling tiles installed between the fixed and reciprocation steps disentangle and aerate the refuse, ensuring a good mixing [110]. The reverse-acting grate design is adopted in Senoko IP, Tuas IP and Tuas South IP. In these systems, the grate is sloped from the feed end to the ash discharge end and the moving grate steps oscillate back and forth in the reverse direction of the flow of the waste. Through this, the waste bed layers at the grate front end are therefore mixed with the red-hot mass from the main combustion zone, leading to a proper tumbling of the waste and good burnout [111]. The proposed grate technology for TuasOne is also the reverse-acting system, considering its long and proven track record in Singapore since 1987. Sembcorp utilizes Dyna-Grate supplied by Babcock & Wilcox Vølund. The grate bars are alternately placed horizontally and vertically, and mounted on shafts. The rotating movement of the shafts directs the grate steps changing from vertical to horizontal and from horizontal to vertical, which produces a wave-like longitudinal movement to transport and agitate the waste [112].

A typical Singapore flue gas cleaning system is consisted of electrostatic precipitators, lime powder dosing equipment and catalytic bag filters to ensure the purified gas to comply with the Environmental Protection & Management (Air Impurities) (Amendment) Regulations 2015, before the exhaust gas is discharged into the atmosphere via 150 m tall chimneys. Singapore tightened the emission standards for CO, NOx, and particular matter from 625, 700 and 100 mg/Nm^3 in the regulation of year 2008–250, 400 and 50 mg/Nm^3, respectively [113]. The emissions limits of cadmium, lead and mercury have also been reduced by at least one magnitude lower (Table S5). The plant detection results in Tuas IP showed that the actual emissions from IPs were by a factor of 2–20 below the legislative standards [106].

After burning, IBA is transported to the ash pit through vibrating conveyors and resource recovery is done by a magnetic separator placed above the conveyor belt to pick up the scrap ferrous metal between 10 mm and 300 mm for sale to the local steel mill for reprocessing into steel products. FA and IBA either quenched or sprayed with water are mixed at the ash pit [114]. The wetted mixture, which makes up to 25% of the incinerated waste by weight, is transferred by truck to Tuas Marine Transfer Station (TMTS) and then delivered to the offshore Semakau Landfill by barge [115]. In July 2015, Singapore opened its first metal recovery facility with a capacity of 1800 t of IBA per day. Since then, IBA from IPs has been further processed at the REMEX metal recovery facility to extract non-ferrous metal (such as aluminium and copper) and the remaining smaller piece of ferrous metal before being landfilled [4]. The facility could reduce the weight of the processed IBA by 10%, in addition to the less than 3% of the reduction in IPs due to the recovery of ferrous scrap only. In 2015, 19,211 t of ferrous scrap was recovered at IPs and 24,000 t of metal was extracted at REMEX, while the remaining 644,629 t ash was landfilled [4].

With the scarcity of land in Singapore, efforts have been continuously spent to maximize the land usage in IP by adopting the space-saving compact design. The land processing capacity almost doubled in the past 20 years, when comparing Keppel Seghers Tuas IP (500 t/day/hectare) with Tuas IP (270 t/day/hectare). The land utilization factor is further escalated in the new TuasOne plant, which could reach 750 t/day/hectare (Table 4).

Ascribing to the technology evolvement and the experience accumulation, significant improvements are also made in Singapore IPs to increase the energy recovery efficiency. In the first IP plant at Ulu Pandan, only 180 kWh of electricity could be harvested from burning 1 t of waste. Currently, the four existing plants produce an average of 450 kWh electricity per tonne of waste incinerated, obtaining a 150% increment in energy conversion efficiency [116]. Considering that Singapore MSW net calorific value is in the range between 7000 and 10,000 kJ/kg, the gross electricity efficiency of current IPs is around 19%. The IPs plant coming online is expected to push the power output to a new level, which is approaching 1000 kWh/tonne or even higher [60]. The electrical efficiency has been improved through a combination of several technologies including, but not limited to, the following approaches.

- Advanced combustion control: A sophisticated and intelligent process control is adopted to maximize waste burnout by optimizing waste feed rate and combustion air distribution [97].
- Raised steam pressure and superheat temperature: Increasing steam pressure and temperature will increase the enthalpy of the stream and allow greater energy to be recovered in the steam turbine. Except Keppel Seghers Tuas IP which is running on the steam condition of 400 °C and 41 bar, the steam generator of the other three electricity generating IPs are operated at 370 °C and 35 bar. In the IWMF IP, the working parameters are set up to 440 °C and 50–60 bar, when the steam leaves the boiler. The downstream superheater fires the biogas from the adjacent sewage sludge digester

Table 5
Economic analysis of the four waste-to-energy options (Values are in Singapore dollars.).

	Plant	AD	Biomass CHP	Gasification	Incineration
	Feedstock	FW	Waste wood	Waste wood	MSW
Cost	Investment cost ($/tonnes)	9.1	4.6	16.6	16.7
	O&M ($/tonnes)	5.5–19.1	4.3–8.6	49.9–59.9	50.1–75.2
	Ash deposit ($/tonne)	–	2.8	0.7	17.3
Revenue	Electricity revenue ($)	42.5	186.9	210	80.5–134.2
	Tipping fee ($/tonne)	77	30	30	77
	By-product sales ($/tonne)	–	134.6 (heat)	83.9 (biochar)	15.5 (metal)
Net revenue ($/tonne)		91.3–104.9	335.5–339.8	246.7–256.7	63.8–142.6

to further boost the steam to 480 °C and 50–60 bar. Additional care with the facility design has also been taken to mitigate the potential erosion and corrosion in the boiler and superheater [60].

- Reduced steam condenser temperature: The condenser temperature plays an important role on turbine efficiency. The lower the condenser temperature, the bigger the temperature difference across the turbine which increases the amount of heat available for conversion to mechanical power. In the current four electricity generating IPs, cooling is conducted by air. Compared with air-cooled condensers, water-cooled condensers could achieve lower temperature and higher efficiency. In IWMF IP, a wet cooling tower with recirculating water is proposed to increase the plant thermal efficiency. However, such cooling towers give rise to water consumption, which is another constraint for Singapore, as it is already stressed with fresh water supply.

3.4.3. Research trend in incineration field

Pulau Semakau Landfill opened in April 1999 and is currently Singapore's only landfill facility, covering an area of 350 ha. In phase I, 193 ha of sea space was converted into 11 landfill cells. In 2015, the development of phase II, occupying 157 ha, was completed, which could meet the disposal needs of Singapore to 2035 and beyond. In view of the lack of alternative landfill in land-scarce Singapore, there is an urgent need to divert the IBA away from the landfill for secondary material utilization. Therefore, the core interest for Singapore researchers is on the potential application of recycled ash.

One of the biggest concerns hindering the wide application and acceptance of IBA lies in its elevated metal concentrations and leaching potential. Residue and Resource Reclamation Centre (R3C) in NTU placed emphasis on characterizing the properties of local IBA and studying the leaching behaviour of IBA when it got into contact with water or even seawater, with the ultimate objective to establish the IBA utilization guideline to regulate the IBA reuse practices [103,117,118]. Yang's research group in NTU investigated the possibility of using IBA in making aerated geopolymer concrete and involving FA in the production of strain hardening cementitious composites [119,120]. Lau's group in NTU proposed to convert hydrothermal treated IBA as a sorbent material or as support for loading cobalt oxide catalysts to treat dye contaminated water [121,122]. Wu's group from Chemilink Technologies Group developed chemical additives to stabilize IBA and transformed it together with marine clay to replace sand as the filling material in land reclamation [123].

The initiative of reality application was taken by Land Transport Authority in 2009 to use processed IBA as the foundation layer of the two 50 m sections of Tampines Road. As part of the trial, the riding quality, structural performance and environmental impact of the road have been under continuous monitoring to assess its long-term stability and leaching potential [124].

3.4.4. Assessment of incineration status in Singapore

Incineration has been conducted in Singapore for almost 40 years since the first Ulu Padan IP is put into commission. State of the art technologies have been successfully applied in local context. The operating experiences accumulated during the past years would provide useful references for other waste managers who are seeking solutions for waste disposal in the megacities. The major obstacle impeding the achievement of higher energy efficiency in Singapore IPs is the inclusion of wet waste especially the FW in the feeding stream, as the humidity lowers the calorific value of the waste and reduces the electric output efficiency. Source separation or centralized mechanical separation is envisioned as a suitable measure to tackle this problem.

IPs expands steam in the turbine to generate electricity. Currently, the heat rejected from the turbine is wasted to air. If waste heat could be captured to provide district cooling or dehumidification or desalination, in contrast to the existent efficiency of 19% in IPs a possible high percentage of the energy value from the waste (approx. 80% in some cases) can be recovered [98]. However, the adoption of heat recovery and supply systems is very dependent on whether a reliable local demand exists for steam or heat. Moreover, there is always a need to balance between the additional capital, operational costs and the revenue from the heat selling.

4. Economical assessment

As the primary goal of a waste-to-energy project is to meet the social requirement for waste management and environmental protection, its installation and operation are not only driven by its ability to make profit. However, the cost-benefit analysis is still of remarkable interests for plant operators and investors. Table 5 summaries the costs and revenues of the four discussed technologies, reported on a per tonne basis. The cost is mainly divided into the capital cost and the O&M costs. The capital cost is the initial investment cost such as land acquisition, equipment and devices procurement, infrastructure construction, etc. The O&M cost is the daily running cost such as the expenses of raw materials, staff salaries, the maintenance of machinery and buildings. The revenues come from the waste tipping fee, electricity export and by-products sales. The detailed calculation methods could be found in the Supplementary materials. Data used was based on local plant data as far as possible.

Two main assumptions were made for the analysis: (1) The cost of waste collection and transportation to the waste-to-energy plant were born by the municipality by charging the corresponding fees from the residences. (2) Due to the lack of reliable data, the following benefits were not taking into consideration: government subsidies, carbon credit through carbon avoidance and tax refund.

As shown in Table 5, the capital cost for AD and biomass CHP plant was 9.1 and 4.6 $/tonne, which was just around half of that of gasification and incineration (16.6–16.7 $/tonne). The O&M cost was also lower in AD (5.5–19.1 $/tonne) and biomass CHP processes (4.3–8.6 $/tonne) than the other two processes (16.6–16.7 $/tonnes). The revenues of treating one tonne of feedstock were highest in biomass CHP process (351.5 $/tonne) with the contribution from electricity sales, heat supplies and tipping fee at 53%, 38% and 9%, respectively. Slightly lower income was found in gasification process (323.9 $/tonne), followed by incineration (173–226.7 $/tonne) and AD process (119.5 $/tonne). The high income and low cost made the biomass CHP process the most profitable one, with the net revenue of treating 1 t of feedstock varying in the range of 335.5–339.8 $. The second most

profitable process was gasification (246.7–256.7 $/tonne), which performed much better than AD (91.3–104.9 $/tonne) and incineration (63.8–142.6 $/tonne).

The results of this analysis should be taken with caution due to the following two reasons: (1) The feedstock was different for the four processes, with each plant targeting a specific waste stream. (2) As gasification technology is not as well established compared to other mature techniques, the results from it may not have the same high level of representativeness and accuracy of the others.

5. Impediment and challenge in waste to energy

As discussed in Section 3, significant energy is embedded in FW and AD is recognized as the most efficient way to maximize the electricity output. However, the first large-scale AD enterprise for FW in Singapore failed, mainly attributed to high inorganic contamination of its FW supply. While the plant was designed to accept FW with impurity level up to 15%, the actual incoming FW contains foreign items above 30% by weight. The business struggled to breakeven, as the operation cost was significantly increased due to sorting and disposing high amount of inorganic waste. The improvement in economical aspect could be realized if better source separation was carried out by the municipality. In addition, application treatment to “dirty” waste, i.e., which derived from mechanical sorting of mixed waste, has often proved to be very critical for the process itself (clogging of the AD reactor due to inert materials, and explosion of digester caused by pressure build up under floating layer etc.) [125,126]. However, the household sorting rate has remained at around 20% despite over a decade of national promoting efforts, which is much lower than Singapore's closer Economies, such as 59.5% in South Korea in 2008 [127], 40% in Hong Kong in 2012 [1] and 37% in Taiwan in 2007 [128].

There are three main reasons which cause a low participation rate among Singaporeans in source separation. Firstly, even having awareness of the current environmental problems, more Singaporean feel them quite occupied as living in a fast-paced environment and have no time for waste sorting. This is unavoidable for a country with no natural resources and only human resources to depend on [129]. Secondly, the ubiquity of refuse chutes placed at the in-house kitchens or lift landings on every level of high-rise public apartments serve as a direct route to the centralised bins at the foot of each block, making it convenient for people to dispose of their waste easily without further separation from the point source. Despite several blue recycling bins are placed under the buildings, people are used to the convenience of rubbish chutes and simply throw away all their unwanted stuffs through it without further efforts on sorting [5]. Thirdly, there is insufficient information on the exact recycling guidelines for people to follow and learn. For example, recycling bins normally display pictures like drinking bottles as an indication for accepting plastic waste. There are many types of plastics in the market which are present in various forms, such as milk bottle, detergent bottle, food trays, plastic bag, egg cartons, cosmetic squeezable bottles, and computer cover. Hence, people are often confused on whether all these plastic wastes could be sorted into the recycle bins or not.

Based on the above findings on the challenges of source separation, the following strategies are suggested to increase waste sorting rate. First, increasing accessibility of recycling facilities could save people's time for transporting sorted materials to the dedicated bins. There are suggestions for the collection bins to be located along frequently used walking routes, for example, the way to the neighbourhood market or along the way to a bus stop. Second, installing properly designed waste separation device could facilitate recycling. Researchers proposed a no-mixed toilet to divert BW to a decentralized AD bioreactor to harness the energy embedded in human waste [37]. Thirdly, utilization of mobile phones and various social media may help to create a large awareness towards an individual's responsibility in waste sorting and convey the right sorting guidelines. For example, a personal and emotional message could be conveyed to people through YouTube, Facebook or Twitter. A phone application could even function more to promote sustainable living, such as sharing news regarding environmental protection, pushing the latest activity about waste recycling and earning rebates through disposing separated waste into designated machines.

6. Conclusion

Singapore is highly reliant on imported natural gas for electricity generation, with 95% of the country's electricity produced by gas-fired power plants. The demand on diversification of fuel mix and mitigation of global warming sparks an eruption of developing renewable energy. Among the plethora of renewable energy sources, MSW, especially the carbon neutral biowaste, is identified as the favourable candidate. Other than gasification which is still under laboratory investigation, AD, combustion-based CHP and incineration have been successfully commercialized. Intensive review on current local WTE practices showed that more electricity could be harvested if wet waste (FW and animal manure) and waste wood could be diverted away from incineration and fed into the anaerobic digester and CHP boiler, respectively. In addition, steam/heat supply generally offers greater opportunity in increasing energy recovery rate in all the WTE plant. However, the availability of suitable customers for steam/heat and relative prices for the supply of the steam/heat play much greater roles in determining the achievable energy efficiency. Potential steam/heat end consumer may include industrial or district heating system, cooling, dehumidification and desalination systems.

One key element for a successful waste to energy scenario is the separation of target waste material followed by an appropriate treatment of each stream in specifically designed plant, as the source segregation allows the highest exploitation of the energy-value from a particular type of waste before it gets contaminated by other waste. However, the failure of Singapore first FW recycling company suggests that significant improvements should be made in facility design and information delivery method to promote garbage source separation among civilians.

Last but not least, remarkable merits can also be appreciated in the aspect of waste to material in WTE systems, such as converting AD digestate into compost product, utilizing wood ash as potassium fertilizer, and applying BA as construction materials. This can not only alleviate the demand on the natural resource but also extend the lifespan of the only landfill in land-scarce Singapore, as the WTE residue is uprecycled rather than passively buried.

Acknowledgement

This research/project is supported by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. Moreover, the authors wish to thank Jermaine Ong and Sukaina Muhamad for their great job in searching and compiling the information about CHP and incineration plant.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2018.09.009.

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